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Nuclear-Spin Quantum Memory Poised to Take the Lead

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To determine how *C. rodentium* establishes enteric infection, Kamada *et al*. compared its ability to colonize pathogen-free conventional mice and germ-free mice (which lack gastrointestinal microbiota). They show that in germ-free mice, the type III secretion system is not necessary for intestinal colonization, whereas it is essential in conventional mice. The authors also show that expression of the type III secretion system occurs in the earlier stages of infection and is reduced at later stages, and that in conventional mice, expression of the type III secretion system plays a key role in intestinal colonization. However, in germ-free mice, even in the absence of the type III secretion system, *C. rodentium* is proficient in intestinal colonization, but is outcompeted by the microbiota in conventional mice. Infection with *C. rodentium* changes the structure of the microbial community, decreasing the number of anaerobes and increasing the numbers of γ-Proteobacteria (*7*). Kamada *et al*. make the seminal observation that *C. rodentium* can be outcompeted by other γ-Proteobacteria such as *E. coli*, but not by *Bacteroides*, and that this competition is governed by carbon source availability. *Bacteroides* is a glycophagic bacterial phylum that can use complex polysaccharides as carbon sources, whereas γ-Proteobacteria (*E. coli* and *C. rodentium*) are restricted to monosaccharides. By shifting the composition of the microbiota toward γ-Proteobacteria (*7*), *C. rodentium* actually undermines its ability to colonize the host by increasing competition for the same nutrient sources. Conversely, this shift in the microbiota composition during *C. rodentium* infection might be a "probiotic strategy" to control enteric infection.

One the major challenges faced by bacteria within communities is acquiring carbon to synthesize primary metabolites. The mammalian gastrointestinal tract harbors trillions of indigenous bacteria whose coexistence relies on the ability of each member to use one or a few limiting resources. Invading pathogens must compete with the microbiota for these resources to establish colonization. These pathogens must be aggressive in their search for a colonization niche, which they achieve by precisely coordinating expression of virulence traits such as the type III secretion system. However, Kamada *et al*. urge us to rethink the concept of type III secretion systems as virulence traits, and to consider whether these molecular syringes may have evolved as tools for niche adaptation in bacterial communities. *C. rodentium* uses its type III secretion system to colonize enterocytes, which is a niche devoid of microbial flora (*10*), allowing it to flourish. However, the shift of microbial composition toward the nutrient-competing γ-Proteobacteria, combined with the reduced expression of type III secretion systems, sets up *C. rodentium* for eventual failure to colonize its host.

The link between carbon metabolism and virulence expression is a key step in the ability of pathogens to recognize suitable sites for colonization, and contributes to the dynamic and volatile interactions between the host, pathogens, and the microbiota. Further insights into these associations may have implications for therapeutic approaches that manipulate their dynamics in diseased or ill states.

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PHYSICS

Nuclear-Spin Quantum Memory Poised to Take the Lead

Isolating a nuclear-spin quantum bit from unwanted interactions with other spins in a solid can extend device memory from seconds to minutes.

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Exploiting quantum mechanics for processing information requires balancing two opposing criteria. Quantum systems must be isolated to prevent decoherence—destruction of the quantum state—but must interact with other quantum systems if the stored information is to be accessed and processed. One way to overcome this challenge is to transfer quantum states between two different systems—one for efficient processing and readout, and the other for long-term storage. Two papers in this issue—by Steger *et al*. on page 1280 (*1*) and Maurer *et al*. on page 1283 (*2*)—show that solid-state quantum memories based on nuclear spin states can have extremely long storage times that approach those of ion traps in a vacuum. This capability is enabled in part by using highly isotopically pure semiconductor materials to make "semiconductor vacuums" that isolate nuclear spins in near solitude.

There are many approaches for quantum information processing (*3*). Those based on isolated spins in semiconductors exploit the wealth of expertise from more than half a century of materials development and processing. They generally follow a similar path. An electron or nuclear spin is localized in a semiconductor, either by incorporating electrostatic gates (*4*) or by using naturally occurring "defects," such as phosphorus donors in silicon (Si:P) (*5*) or nitrogen-vacancy (NV) centers in diamond (*6*). Applying a magnetic field then allows the eigenstates of the spin to be used as a logical basis for storing quantum information—a quantum bit (qubit). Serendipitously, during the early development of spin-resonance techniques, ensembles of such isolated spins in semiconductors were studied, revealing extremely long phase-coherence times (orders of milliseconds were already observed half a century ago), which now motivate the use of these systems for quantum technologies.

Quantum information processing requires qubit initialization, control, and readout. For NV centers, luminescence provides for optical single-spin readout (*6*). In silicon, optical spectroscopy and electric

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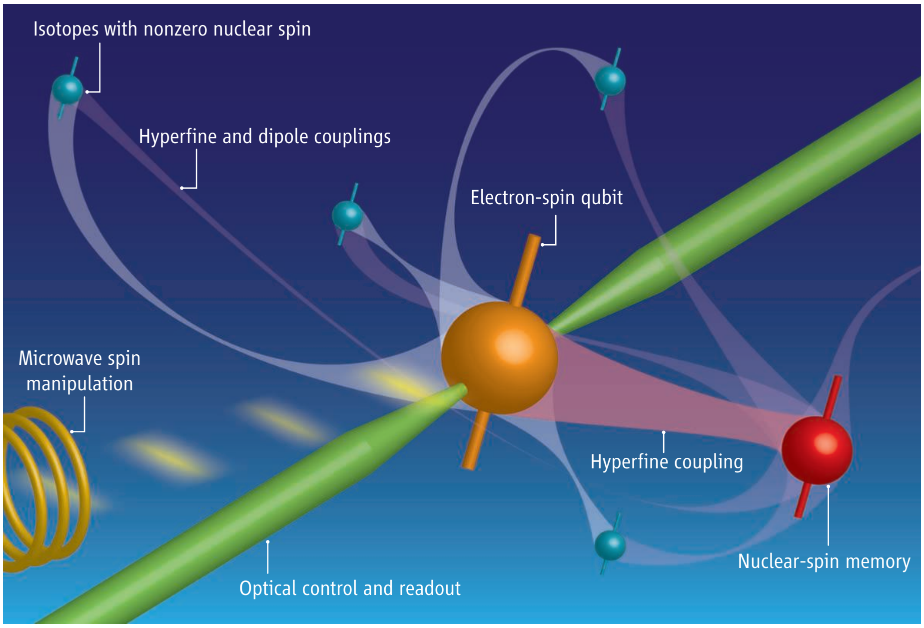

Nuclear-spin–based quantum memory. The quantum bits created in diamond by Maurer *et al.* and in silicon by Steger *et al.* can both be read out optically, and both couple to nearby nuclear spins, which can be used as a long-lived quantum memory. Both types of qubits are contained in crystals that naturally include isotopes of silicon (^{29}Si) and carbon (^{13}C), which contribute unwanted spins, leading to decoherence of the quantum memories. Isotopic engineering can substantially reduce this background, which, when combined with dynamic decoupling sequences and control of the hyperfine coupling between qubit and quantum memory, can result in quantum storage for more than 3 min for ^{29}Si.

currents have been used to read ensembles of isolated spins (*1*, *7*), and recently such approaches have been scaled to the single-spin limit (*8*). Spin resonance techniques are generally used for control.

Stored quantum information must also retain its "quantumness" on time scales that allow information processing. Spins couple easily to other spins in their local environment, which can extend for hundreds of nanometers. Both carbon and silicon have isotopes with nuclear spin, and interactions between spin qubits and these unwanted spins limit coherence. To overcome these environmental perturbations, both studies reported here use isotopically engineered materials—the pure silicon ^{28}Si comes from the Avogadro project (*9*). The aim is to remove all nuclear spins that can cause decoherence—except one.

It is this sole remaining nuclear spin that lies at the heart of these approaches. Because of their small size (femtometer scale) and their small magnetic moments, nuclear spins are much more isolated than electron spins and have correspondingly longer coherence times, which has led to them being recognized as ideal systems in which to store quantum information (*7*, *10*–*12*). In the two experiments described in this issue, a nuclear spin is coupled to an electron qubit via the hyperfine interaction (see the figure). Using careful control sequences, the quantum state of the electron qubit can be transferred to the nuclear spin, stored there for some time, and then transferred back again (*12*) or read out directly. Maurer *et al.* used a ^{13}C nucleus ~1.7 nm from the NV center, whereas Steger *et al.* used a ^{31}P nucleus and its very own donor electron spin. In both cases, dynamic decoupling sequences, which manipulate the nuclear spins in an acrobatic fashion to compensate environmental fluctuations, were used to remove the impact of the trace amounts of remaining impurities.

Quantum memory must be isolated from the outside world as much as possible. Thus, the hyperfine interaction used for the quantum states transfer seems a glaring problem. Indeed, both the quantum memories reported here are limited by spin-flip relaxation time (T_1) of the electron qubit (which is much longer in silicon than in diamond), mediated by the hyperfine interaction. However, this interaction is needed only for the transfer of quantum information in and out of the memory, and Maurer *et al.* present an elegant method for controlling this interaction by optically exciting the electron into a state that has no spin, and no hyperfine coupling, to the nuclear memory. This method allowed them to extend the lifetime of their quantum memory by nearly two orders of magnitude, to ~1 s. Recently, Dreher *et al.* (*13*) demonstrated that this approach can also be effective in extending the coherence of Si:P-based qubits by optically ionizing the ^{31}P donor.

So, in the end, how good are these memories? With isotopic purification and dynamic decoupling, quantum states were stored in a ^{31}P ensemble for more than 3 min [compared with ion trap lifetimes in the second-to-minute range (*3*)]. This remarkable achievement advances nuclear spins in silicon as one of the most coherent systems in nature. It will be interesting to see if this time scale can be maintained when the infrastructure necessary for single-donor readout is incorporated near a single nuclear spin.

The ^{13}C-based nuclear memory, with a storage time of 1.4 s, might seem less impressive, but such an opinion would vastly undervalue this result, which is observed at room temperature and on a single quantum system. Indeed, with the ability to entangle NV centers and photons (*14*), and progress toward entangling distant NV centers (*15*), the availability of an isolated, long-lived nuclear-spin quantum memory represents an important advance for this technology. Maurer *et al.* conclude on an extremely optimistic note, estimating (quite rigorously) that improvements to the isotopic purity of diamond, the hyperfine decoupling, and the dynamic decoupling may result in quantum storage times exceeding 1 day. Such long-lived quantum systems could disruptively change the way we think of information security. Quantum-secured tokens could prevent credit-card skimming or be incorporated into provably unforgeable identity cards.

Solid-state nuclear-spin quantum memory is progressing rapidly, and the two studies described here show that it may well be the most effective way to store quantum information. The demonstration of quantum coherence lasting for time scales relevant to real-world conditions holds promise for as yet unimagined quantum-enabled technology becoming as ubiquitous as classical electronics are today.

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